Threshold effects in pulsed NMR in superfluid ^{3}He-B

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Experiments on pulsed NMR in ^{3}He-B in plane-parallel geometry are performed. The excitation of the induction signal has a threshold nature and the induction signal frequency is equal to the Larmor frequency.

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In free ^{3}He-B, the spin precession frequency is equal to the Larmor frequency for deflection angles of the nuclear magnetization less than 104°.[1,2] In this case, the vector **n** precesses together with the magnetization vector. The walls have a strong effect on the orientation of the vector **n**. If, in the unperturbed state, $\mathbf{n}\|\mathbf{H}$ (**H** is a constant external magnetic field) far from the walls, then in direct proximity of the walls, situated parallel to **n** and precisely at a distance from the walls less than the so-called magnetic length R_H, the vector **n** forms some angle with the surface of the wall determined from the condition

$$\cos^2\phi = 1/5\,. \tag{1}$$

As a result, the NMR frequency is shifted from the Larmor frequency and for a given angle ϕ, it is determined from the equation[3,4]

$$\omega^2 = \frac{1}{2}[\,\omega_0^2 + \Omega_B^2\,] + \{\frac{1}{4}(\,\omega_0^2 + \Omega_B^2)^2 - \omega_0^2\,\Omega_B^2\cos^2\phi\}^{1/2}, \tag{2}$$

where ω_0 is the Larmor frequency, and Ω_B is the longitudinal resonance frequency.

Experiments on continuous NMR in a chamber containing ^{3}He, filled with a collection of plane-parallel plates separated by a distance less than R_H and with the external magnetic field oriented parallel or at some angle to the surface of the plates were performed in Refs. 5 and 6. It turned out that the NMR frequency is shifted relative to the Larmor frequency in exact correspondence with Eq. (2). The purpose of our work was to investigate the pulsed NMR signals in ^{3}He-B in an analogous geometry. In this case, Eq. (2) generally is no longer valid, so that for pulsed NMR we have large spin deflection angles away from the direction of the external magnetic field and the related Zeeman energy can greatly exceed the surface energy, deflecting **n** away from **H**.

The experimental volume with ^{3}He was a rectangular parallelepiped with dimension $5.5\times5.5\times10$ mm and was filled with a collection of equally spaced plates made of thin (12 μm) dacron. The distance beteween the plates was 0.3 mm. The external constant magnetic field was oriented parallel to the plates. The experiments were performed in fields of 77 and 154 Oe. Under these conditions $R_H \approx 1$ mm, i.e., we can assume that in equilibrium the texture of the vector **n** is uniform in the space between the plates and, in addition, the vector **n** everywhere forms an angle ϕ with the direction of the external constant field, determined from condition (1).

All experiments were performed at a pressure of 29.3 bar and in the temperature range 0.48–0.74 T_c. We measured the temperature with a platinum PLM-3 thermometer, calibrated according to the temperature of the ^{3}He transition in the superfluid state. The required temperature was achieved with the help of a nuclear demagnetization cryostat.

The experiments were performed as follows.

The measuring circuit was tuned to a fixed frequency (250 or 500 kHz) and then, as the external magnetic field was slowly scanned, radio frequency (rf) pulses were applied periodically. The amplitude of the field of the rf pulses was 2 Oe. The signal from the ^{3}He spins was recorded with the help of a Datalab-905 digital oscillograph with memory, which permitted measuring the frequency of the signal as well. It turned out that the induction signal arises in a threshold manner: for rf pulse with short duration, no induction signal was observed, but when the duration of the rf pulse exceeded $\sim 20\,\mu$s even slightly (which corresponds to rotation of the magnetization by $\sim 40°$ in the case of normal ^{3}He), the amplitude of the induction signal increases sharply (Fig. 1). To obtain a quantitative measure of the amplitude of the induction signal, the signal was integrated over the interval 0.8 to 1.1 ms after termination of the rf pulse. The peak of the signal in a given field depended strongly on the duty factor of the pulse and the optimum rf pulse frequency in turn depended on temperature and varied from 550 to 530 kHz in a field of 154 Oe with the temperature varying from 0.5 to 0.7 T_c (Fig. 2). The threshold duration of the pulse, however, was nearly independent of the rf pulse frequency and temperature. In addition, the frequency of the induction signal always was equal to the Larmor frequency (i.e., it is equal, for example, to 500 kHz in a 154-Oe field and changes with the external field. On the other hand, the frequency of the continuous NMR signal is displaced strongly from the Larmor frequency in accordance with Eq. (2).

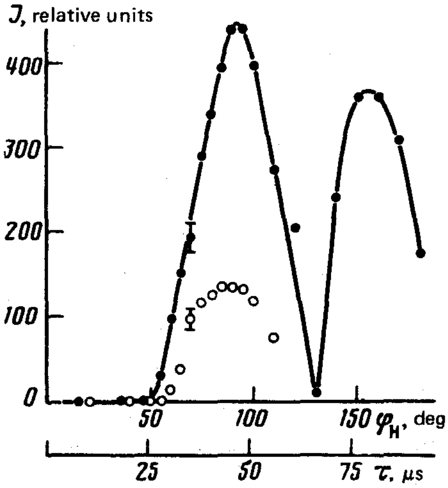

FIG. 1. Dependence of the induction signal intensity on the rf-pulse duration (τ) in a magnetic field $H = 154$ Oe: ϕ_H is the angle of rotation of magnetization in normal ^{3}He by a pulse of corresponding length; ●—$T/T_c = 0.61$; ○—$T/T_c = 0.49$.

For excitation pulse durations from 20 to 40 μs, one more unexpected effect was observed. The induction signal did not have a completely regular nature: small "dips" or "humps" were observed against the background, monotonic drop in signal level. It turned out that two stable forms of the induction signal exist, which regularly follow each other when a series of identical pulses are applied; this effect remained even with a delay of one hour between the two neighboring pulses.

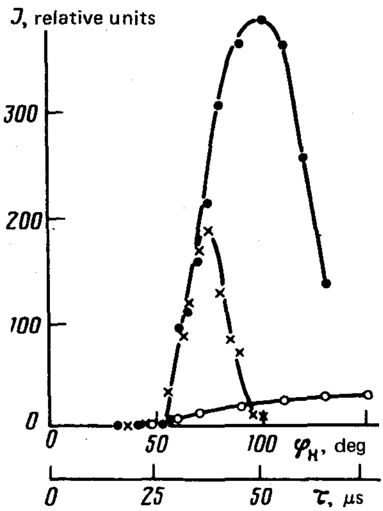

FIG. 2. Dependence of the induction signal intensity on the duration of the rf pulse at a temperature 0.55 T_c; ●—$f = 540$ kHz; ×—$f = 550$ kHz, and ○—$f = 500$ kHz.

The threshold in the dependence of the induction signal intensity on the duration of the exciting pulse can be explained as follows: Eq. (2) can be assumed to be correct only for very small deflection angles of the magnetization away from the external field; for sufficiently large deflection angles, the precession at a frequency shifted from the Larmor frequency evidently becomes unstable and the system goes over in a threshold manner in the Larmor frequency, corresponding to the other solution of the Legget equations, which is usually realized in experiments with ^{3}He in a large volume (i.e., the effect of the walls can be ignored). This assumption is confirmed by numerical solution of the Legget equations, which for our case was obtained by Leman and Galo. The nature of the sequence of induction signals still remains unclear.

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